AN EXPERIMENTAL STUDY ON THE SEISMIC PERFORMANCE OF POST-INSTALLED REINFORCED CONCRETE-MASONRY COMPOSITE WALL

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ABSTRACT

Masonry structures are widely used in residential and public architectures, especially some seismic regions in China before the 1990s. The failure of masonry structures is influenced by several factors, e.g. material properties of brick and mortar, geometry of brick, joint thickness, properties of bond of brick and mortar, etc. These masonry structures, built in early stage, cannot satisfy the seismic requirement. Retrofitting existing masonry structures by installing the reinforced concrete members around the masonry structure is a new retrofit method. This method can not only improve the strength, but also improve the stiffness of the masonry structures. The longitudinal and the transverse composite walls were constructed under cyclic loading test. The test specimens were composed by masonry wall and RC element. The ultimate bearing capacity, ductility, hysteresis characteristic, stiffness degradation and damage pattern are analyzed in this paper. The conclusions are as follows: the connecting joint, pull (shear) bar and embedded bar, presented in this paper, have good connection capacity. The composite wall has good capacity of load bearing and deformation. By the analysis of equivalent viscous damping coefficients, the energy dissipation capacity of masonry wall is improved by post-installed concrete wall.

KEYWORDS: *composite wall, cyclic loading tests, bearing capacity, ductility, damage pattern, energy dissipation*

INTRODUCTION

Masonry structures are known for their low cost, simple construction technique and rapid construction speed, has been widely used in residential and public buildings. As a special structure type, reinforced concrete-masonry composite wall has been studied by many researchers. Gao et

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al. analyzed the performance of the composite structure with 1: 2 scaled model test [1]. The results showed that the 8-story composite structure with brick and reinforced concrete walls has good seismic behavior, which satisfies the requirements of seismic fortification in 8 seismic intensity region; the composite structure has the characteristics of flexure and shear deformation; the brick wall and reinforced concrete wall have a good cooperative characteristics. According to the experimental research, Gao summarized the characteristics of the force, failure mode and ultimate carrying capacity of the composite structure, evaluated the seismic performance, and proposed seismic design requirements of this structure type [2]. Wang et al. [3] and Shi et al. [4] developed a program MRCSAI.0 using VC++ and FORTRAN language to analyze the nonlinear seismic response of reinforced concrete-masonry composite structure. The seismic performance of a composite structure example under earthquake loading is evaluated using MARCSAI.0, which verified the feasibility and reliability of the software. Sun et al. [5] studied the cooperative working performance of masonry wall-reinforced concrete wall composite structures. The influence of shear deformation of concrete wall and coupling beam on the seismic analysis was discussed. It is shown that both of the cooperative characteristics and shear deformation of the reinforced concrete wall should be considered in the seismic analysis.

The above researches focused on newly built constructions, the cooperative work performance of masonry wall and concrete wall can be easily achieved in the planning constructing project. For the existing masonry structure, this paper proposed a new retrofitting method by installing the reinforced concrete members around the masonry structure to take fully advantage of vertical compressive capacity of original masonry structure and horizontal resisting capacity of reinforced concrete wall and to enhance the integrity and ductility of the exiting masonry structure, preventing collapse under rare earthquake.

The cooperative working ability between masonry walls and post-installed concrete walls, depending on the reliable connection between these, is the key factor to guarantee the ductility and stiffness of the composite structure under rare earthquake. Based on the previous researches [6-9], the seismic performance of the composite structure and the reliability of connection joints were studied through a series of cyclic loading test, including six composite walls. The ultimate bearing capacity, ductility, hysteresis characteristic, stiffness degradation, dissipation capacity and damage pattern are investigated in this paper.

EXPERIMENTAL INVESTIGATION

Specimen Description

The specimens were designed. Six specimens including three same transverse composite walls (BWH-1 to BWH-3) and three same longitudinal composite walls (BWZ-1 to BWZ-3) were designed and tested in this experiment. The size of the longitudinal composite wall is 3.75m×1.55m. In this test, the size of masonry wall is 3.00m×1.55m. The size of RC element is 1.550m×0.375m. The size of the transverse composite wall is 2.55m×1.55m. In this test, the size of masonry wall is 3.00m×1.55m. And the size of RC element is 1.550m×0.30m. The thicknesses of masonry wall and RC element are 0.12m. The composite walls are shown in Figure 1.

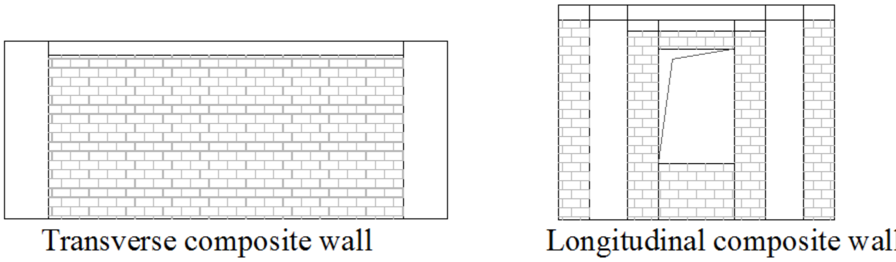
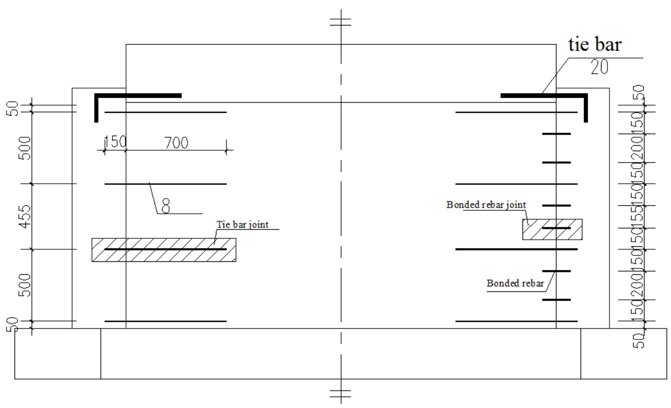


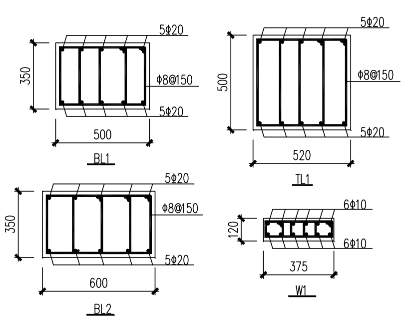
Figure 1: Equivalent Progress of Composite Wall

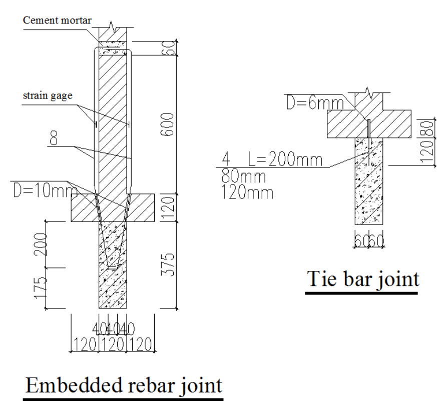
Construction of Specimens

Flemish bond and English bond are two typical brick laying in China. Thus BWH-1, BWH-2, BWZ-1 and BWZ-2 were constructed using Flemish bond, while BWH-3 and BWZ-3 were constructed using English bond for comparison. The masonry wall were constructed of MU10 Fried Common Brick and M2.5 Mixed Mortar. The dimensions of block used for construction are 120mm×57mm×26mm.Details and reinforcement of test specimens are shown in Figure 2, Figure 3 and Figure 4.



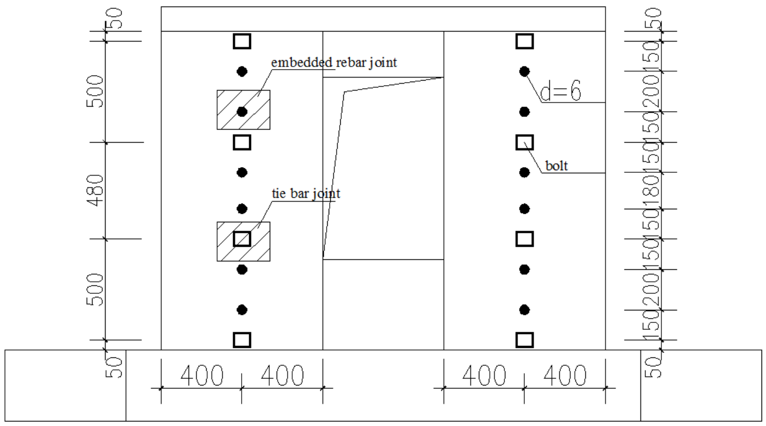
(a) Binding steel bar details of specimen BWH



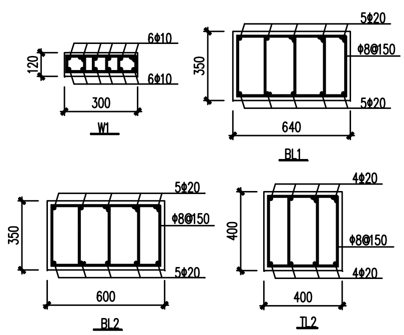


(b) Reinforcement details of specimen BWH (c) Details of connection joint (specimen BWH)

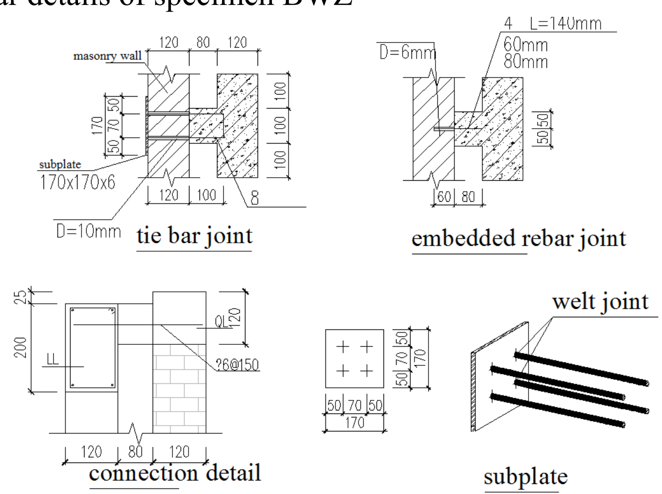
Figure 2: Details and Reinforcement of Test Specimens BWH



(a) Binding steel bar details of specimen BWZ



(b) Reinforcement details



(c) Details of connection joint (specimen BWZ)

Figure 3: Details and Reinforcement of Test Specimens BWZ

Figure 4: Construction of connection joint

Material Properties

The material properties of Fried Common Brick, Mixed Mortar, concrete and steel bar were obtained through material property testing, as shown in Table 1 and Table 2.

Table 1: Material Properties of Masonry Walls

Specimen Number	Bonding Method	Brick Compressive Strength (MPa)	Mortar Compressive Strength (MPa)	Masonry Compressive Strength (MPa)	Masonry Shear Strength (MPa)	Concrete Compressive Strength (MPa)
BWH-1	Flemish bond	9.54	2.51	2.14	0.21	27.1
BWH-2	Flemish bond		2.34	2.31	0.21	
BWH-3	English bond		1.50	1.75	0.14	
BWZ-1	Flemish bond		2.23	2.13	0.13	
BWZ-2	Flemish bond		2.19	2.27	0.20	
BWZ-3	English bond		1.21	1.83	0.19	

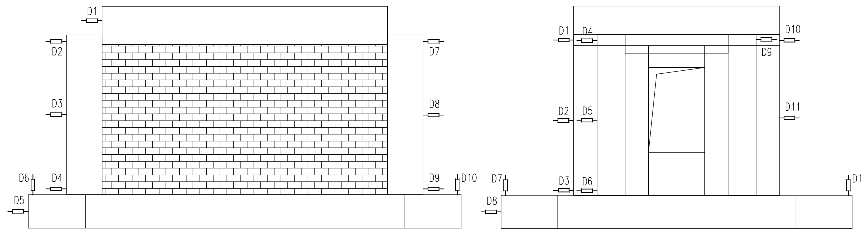
Table 2: Material Properties of Steel Bars

Position	Rebar Diameter (mm)	Yielding Strength		Ultimate Strength	
		Load (kN)	Strength(MPa)	Load (kN)	Strength(MPa)
Longitudinal steel bar of beam and column	12	35.6	314.9	38.7	342.4
	10	26.2	333.8	25.8	328.7
Stirrup	6	6.2	219.4	7.4	261.9
Bonded rebar of wall	4	3.9	310.5	4.7	374.2
Tie bar	8	11.2	222.9	12.5	248.8

Test Setup and Procedure

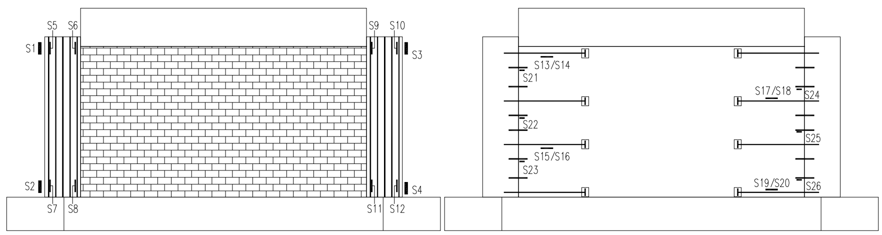
These tests were conducted under displacement-controlled cyclic loading test in the State Key Laboratory at Tongji University. The specimens were cyclic thrice at each displacement level with displacement increments of 1.5mm up to cracking of the masonry wall. The application of lateral displacements were then followed by cycles with increments of the cracking displacement. The loading process continued until the failure of the walls or the strength of the specimens decreased to 85% of the peak lateral load. Extra vertical loads were applied by hydraulic jacks at the top of the specimens to simulate gravity loadings. 180kN vertical load (equivalent wall pressure 0.50MPa) was applied to specimen BWH-1, BWH-2 and BWH-3. 100kN vertical load (equivalent wall pressure 0.52MPa) was applied to BWZ-1, BWZ-2 and BWZ-3.

Arrangements of displacement meter and strain gages are presented in Figure 5 and Figure 6. In order to study the stress and deformation performance of concrete walls and masonry walls, the strain gages and LVDTs were installed, respectively. The strain gauges were set up on bonded bar and tie bar to analyse the mechanical behavior of the connecting joints.

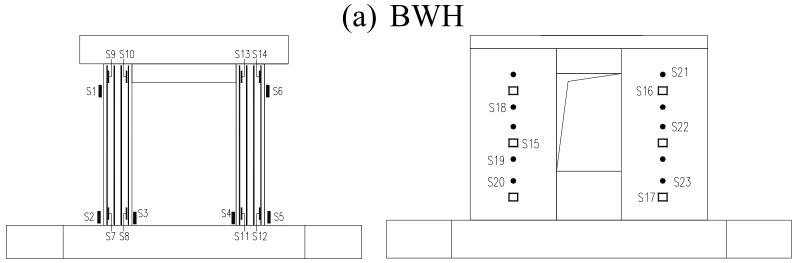


(a) BWH (b) BWZ

Figure 5: Position of LVDTs



(a) BWH



(b) BWZ

Figure 6: Position of Strain Gauges

TEST RESULTS AND DISCUSSION

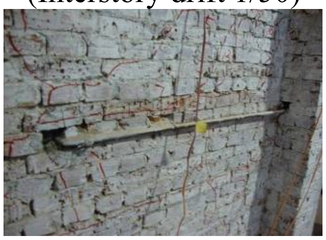
Failure Mode

As the damage patterns of BWH specimens were similar, the damage progression of BWH-2 was given in Figure 7. The behavior of lengthwise composite walls was dominated by shear response. X shape cracks crossed through the grout filled blocks at low displacement levels. With increased displacement, stepped cracks passing through the mortar joints. Formed and diagonal cracks crossing through the concrete wall were seen, indicating that connection capacity of connecting joint to ensure cooperative work between masonry walls and concrete walls. As loading continued to 16mm, wide horizontal bed joint cracks were clearly visible at the wall end under tension. As loading continued to 35mm, crumbling of the masonry wall occurred at the wall toes along the out-of-plane distortion of the face shell.

(a) Brick Fracture (out-of-plane distortion)
(Interstory drift 1/50)

(b) Crack of Masonry Wall
(Interstory drift 1/50)

(c) Crack of Concrete Wall
(Interstory drift 1/50)



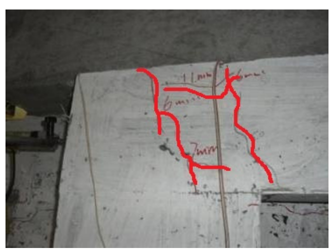
(d) Connecting Joint Failure
(Interstory drift 1/100)

(e) Failure on Bottom of Concrete Wall
(Interstory drift 1/50)

(f) Failure on Top of Concrete Wall
(Interstory drift 1/100)

Figure 7: Typical Damage of BWH-2

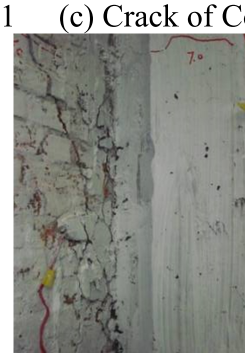
(a) Crack of Masonry Wall



(b) Crack of Concrete Wall 1

(c) Crack of Concrete Wall 2

(d) Failure on Connecting Joint



(e) Failure on Connecting Joint

(Interstory drift 1/100)

Figure 8: Typical Damage of BWZ-1

As the damage patterns of BWZ specimens were similar, the damage progression of BWZ-1 was given in Figure 8. Inclined cracks formed in the masonry face shells at the corner of the window and the wall-beam joint of the concrete wall, along with the horizontal cracks at low displacement levels. With increased displacement, widening of the cracks in the concrete wall occurred. Further splitting and eventually crushing at the concrete wall toes in the compression end occurred along wide horizontal bed joint cracks were clearly visible at the masonry wall, as loading reached to 8mm.

Hysteretic Curves

The hysteretic curves of all the six specimens are shown in Figure 9. All the walls response were almost linear elastic up to the crack of the walls which resulted in thin hysteresis loops with low energy dissipation. However, at large displacement, the loop became larger, indicating higher energy dissipation. With increased lateral displacement, stiffness degradation gradually occurred, as shown from the flatter loading curve for each new cycle. The behavior of all walls was dominated by shear response. However, the stiffness and energy dissipation capacity of lengthwise composite wall were better than cross composite wall, as shown in Figure 9.

Skeleton Curves

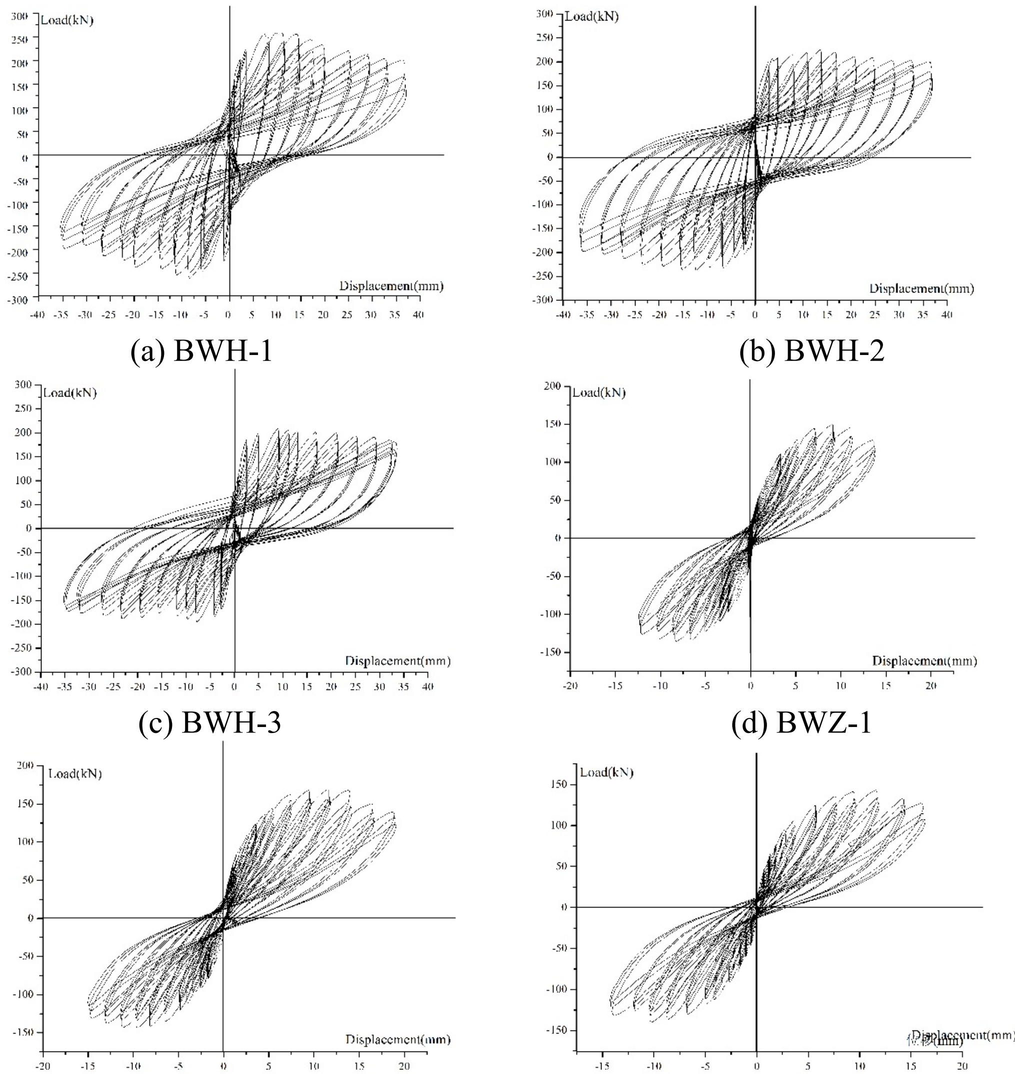
Figure 10 illustrates the definition of yield and ultimate displacements. Figure 11 compares the skeleton curves of specimens. Cracking load P_c, cracking displacement Δ_c, peak load P_p, corresponding displacement Δ_p, ultimate load P_u, ultimate displacement Δ_u and ductility ratio can be estimated from the skeleton curves (Table 3). The test results showed that ultimate bearing capacity and deformation capacity of the concrete-masonry composite wall are greatly improved.

Ductility Ratio

The displacement ductility ratio μ is given as:

$$\mu = \frac{\Delta_u}{\Delta_y} \qquad (1)$$

where, Δ_u and Δ_y are ultimate displacement and yielding displacement, respectively. The ductility ratios of each specimen are shown in Table 3. The ductility ratio of masonry walls is around 2.0 [10] [11]. As seen from Table 3, the capacity of load bearing and the ductility of the wall can be improved by post-installed concrete wall.



(a) BWH-1 (b) BWH-2

(c) BWH-3 (d) BWZ-1

(e) BWZ-2 (f) BWZ-3

Figure 9: Hysteretic Curve of Cross Composite Wall

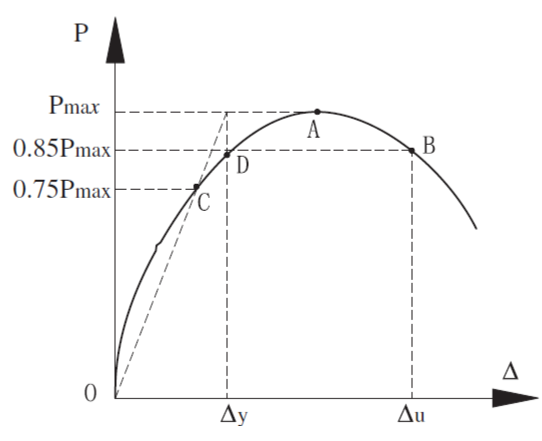
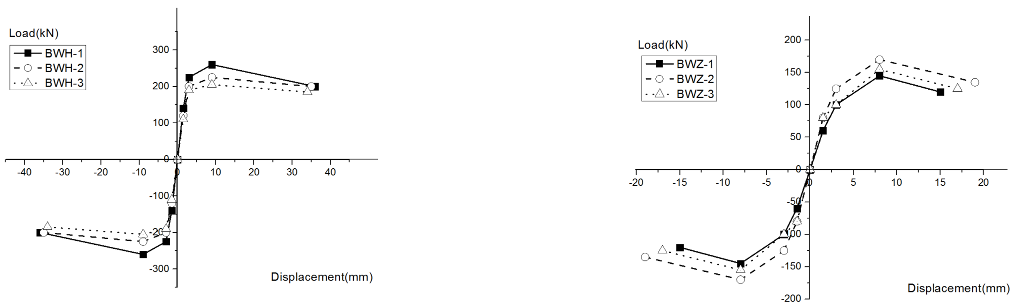


Figure 10: Definition of Yield and Ultimate Displacements

Table 3: Bearing Capacity and Displacement of Test Specimens

Specimen Number	Crack Point		Yielding Point		Peak Point		Ultimate Point		Ductility Ratio
	P_c (kN)	Δ_c (mm)	P_y (kN)	Δ_y (mm)	Δ_p (kN)	Δ_p (mm)	P_u (kN)	Δ_u (mm)	
BWH-1	140	1.5	225	3	260	9	200	36	12.00
BWH-2	120	1.5	200	3	225	9	200	35	11.67
BWH-3	110	1.5	190	3	205	9	185	34	11.33
BWZ-1	60	1.5	100	3	145	8	120	15	5.00
BWZ-2	80	1.5	125	3	170	8	135	19	6.33
BWZ-3	80	1.5	100	3	155	8	125	17	5.67



(a) BWH (b) BWZ

Figure 11: Skeleton Curves of Test Specimens

CONCLUSION

By the results of experiment, the conclusions are as follows:

(1) As seen from the failure mode, the tie bar and the bonded bar were applied to ensure the cooperative work between the post-installed concrete wall and the masonry wall under horizontal load. The results indicate that the installed connecting joint is safe and reliable.

(2) The composite wall has good capacity of load bearing and deformation as seen from the hysteretic curves and skeleton curves. The ultimate shear strength of transverse composite members was more than 200kN, and the ultimate bearing capacity of longitudinal composite members was above 145kN. The ductility coefficient of transverse and longitudinal composite members were 11 and 5, respectively.

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